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DETECTION OF SUPERNOVA NEUTRINOS* **

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Matter effects on neutrino oscillations in both, a supernova and the Earth, change the observed supernova neutrino spectra. We calculate the expected number of supernova neutrino interactions for ICARUS, SK and SNO detectors as a function of the distance which they traveled in the Earth. Calculations are performed for supernova type II at 10 kpc from the Earth, using standard supernova neutrino fluxes described by thermal Fermi–Dirac distributions and the PREM I Earth matter density profile.

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1. Introduction

Iron is the most strongly bound of all elements which means that fusion and fission reactions result in the absorption, rather than the production, of energy. The last stage of a massive star life (mass $> 10M_{\odot}$) is the collapse of its Fe core (the whole core material has already been transformed, via the chain of nuclear reactions, into Fe). This happens when the mass of the Fe core exceeds the Chandrasekhar limit ($\sim 1.45M_{\odot}$ if one takes equal numbers of neutrons and protons, [1]) — a supernova (SN) type II birth is a fact. It starts to explode. All flavors of neutrinos are radiated away in the form of two bursts of the duration of milliseconds and seconds. The emitted neutrinos carry almost all ($\sim 99\%$) of the SN binding energy ($\sim 10^{53}$ erg).

The only observed, up to now, burst of SN neutrinos came from the SN1987A which had exploded in the Large Magellanic Cloud, at the distance of about 52 kpc away from the Earth. Due to this distinct distance,

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the reconstruction of only 19 events of the neutrino interactions by the Kamiokande [2] and IMB [3] water Cerenkov detectors had been possible. But, it was enough to confirm the main features of the models of SN explosion.

Neutrinos, on their way from the production point inside the SN high dense Fe core to the terrestrial detector, interact with matter. Non-zero neutrino masses, together with flavor mixing enhanced by matter effects, result in considerable differences in neutrino fluxes between the production and the detection points. Systematic studies of the number of SN neutrino interactions in three detectors, ICARUS [4], SK [5] and SNO [6], as a function of the distance passed by neutrinos in the Earth is the aim of this work.

2. Neutrino fluxes from a supernova

A supernova is a source of fluxes of neutrinos and antineutrinos of all three flavors (e , μ , τ). The neutrino/antineutrino energy spectra at the production point (*i.e.* inside the SN) of various flavors can be described by the thermal Fermi–Dirac distributions (all chemical potentials set to zeros, see [7]):

$$F_{\alpha}^0(E, T_{\alpha}, L_{\alpha}) = \frac{L_{\alpha}}{T_{\alpha}^4 F_3} \frac{E^2}{e^{E/T_{\alpha}} + 1},$$

where $\alpha = \nu_e, \nu_{\mu}, \nu_{\tau}, \bar{\nu}_e, \bar{\nu}_{\mu}, \bar{\nu}_{\tau}$. Here, E represents energy of the neutrinos, L_{α} is the total energy released in various flavors of neutrinos ($L_{\alpha} \simeq E_B/6$, with $E_B \simeq 3 \times 10^{53}$ ergs — binding energy emitted in the core collapse of the star), F_3 is a normalizing constant given by $F_3 = 7\pi^4/120$, T_{α} is the temperature of the ν_{α} gas in the neutrino sphere. We assume the following hierarchy of temperatures: $T_{\nu_e} = 3.5$ MeV, $T_{\bar{\nu}_e} = 5$ MeV, $T_{\nu_x, \bar{\nu}_x} = 8$ MeV, where ν_x and $\bar{\nu}_x$ mean ν_{μ}, ν_{τ} and $\bar{\nu}_{\mu}, \bar{\nu}_{\tau}$, respectively.

Neutrinos produced deep inside supernova, before escaping from the star, interact with the matter of its mantle. Thus, transitions of neutrino species can occur. These oscillations of neutrinos in supernova are considered here according to [8]. The conversions take mainly place in two resonance layers in the outer regions of a supernova mantle. There is a high density resonance region (H resonance layer) — $\rho_H \approx 10^3\text{--}10^4$ g/cm³, and low density resonance region (L resonance layer) — $\rho_L \approx 10\text{--}30$ g/cm³. Transitions in the H resonance layer are governed by atmospheric neutrino oscillation parameters: Δm_{31}^2 and Θ_{13} , whereas transitions in the L resonance region are governed by solar neutrino oscillation parameters: Δm_{21}^2 and Θ_{12} . The transition probabilities (between two neutrino mass eigenstates) in the resonance layers are called the *flip probabilities* — P_H, P_L for neutrinos and \bar{P}_H, \bar{P}_L for antineutrinos.

The final total neutrino/antineutrino mass eigenstates fluxes on a supernova surface ($F_i, F_{\bar{i}}, i = 1, 2, 3$) are given by the following sets of equations ($F_\alpha^0, F_{\bar{\alpha}}^0$ are the initial total production fluxes defined above, respectively, $e \rightarrow \nu_e, \bar{e} \rightarrow \bar{\nu}_e, x \rightarrow \nu_\mu$ or $\nu_\tau, \bar{x} \rightarrow \bar{\nu}_\mu$ or $\bar{\nu}_\tau$).

For Direct (normal) mass hierarchy ($m_1 < m_2 \ll m_3$):

$$\begin{aligned} F_1 &= P_H P_L F_e^0 + (1 - P_H P_L) F_x^0, \\ F_2 &= (P_H - P_H P_L) F_e^0 + (1 - P_H + P_H P_L) F_x^0, \\ F_3 &= (1 - P_H) F_e^0 + P_H F_x^0, \\ F_{\bar{1}} &= (1 - \bar{P}_L) F_{\bar{e}}^0 + \bar{P}_L F_{\bar{x}}^0, \\ F_{\bar{2}} &= \bar{P}_L F_{\bar{e}}^0 + (1 - \bar{P}_L) F_{\bar{x}}^0, \\ F_{\bar{3}} &= F_{\bar{x}}^0. \end{aligned}$$

For Inverted mass hierarchy ($m_3 \ll m_1 < m_2$):

$$\begin{aligned} F_1 &= P_L F_e^0 + (1 - P_L) F_x^0, \\ F_2 &= (1 - P_L) F_e^0 + P_L F_x^0, \\ F_3 &= F_x^0, \\ F_{\bar{1}} &= (\bar{P}_H - \bar{P}_H \bar{P}_L) F_{\bar{e}}^0 + (1 - \bar{P}_H + \bar{P}_H \bar{P}_L) F_{\bar{x}}^0, \\ F_{\bar{2}} &= \bar{P}_H \bar{P}_L F_{\bar{e}}^0 + (1 - \bar{P}_H \bar{P}_L) F_{\bar{x}}^0, \\ F_{\bar{3}} &= (1 - \bar{P}_H) F_{\bar{e}}^0 + \bar{P}_H F_{\bar{x}}^0. \end{aligned}$$

A complete discussion of how to calculate flip probabilities can be found in [8]. For the purpose of this paper we will only state here that, in case one considers the LMA (Large Mixing Angle) neutrino oscillations parameters: $P_L = \bar{P}_L = 0$ and, in the so called *Large* Θ_{13} case ($\sin^2 \Theta_{13} > 3 \times 10^{-4}$, the so called region I in [8]): $P_H = \bar{P}_H = 0$, while in the so called *Small* Θ_{13} case ($\sin^2 \Theta_{13} < 2 \times 10^{-6}$, the so called region III in [8]): $P_H = \bar{P}_H = 1$ (it is interesting to notice here that, in this case, the resulting fluxes are equal for both, Direct and Inverted, mass hierarchies).

The finite spread of the neutrino wave packets, together with the small value of their coherence length and the large distance from supernova to the Earth, imply that neutrinos arrive to the surface of the Earth as fluxes of incoherent mass eigenstates.

Thus, the above equations describe also (except for a simple geometrical factor related to the distance between a supernova and the Earth) the neutrino/antineutrino mass eigenstates fluxes at the surface of the Earth (because there is no matter on the way between a supernova and the Earth, there can be no additional transitions between neutrino mass eigenstates).

3. Earth matter effect

In order to calculate oscillation probabilities we used the standard description of neutrino regeneration effect in the Earth [9]. The numerical calculations were made with use of the CERN library function DEQBS. We applied the realistic Earth matter density profile PREM I [10, 11].

The following LMA I (Large Mixing Angle) neutrino oscillation parameters were used (note the two values of the $\sin^2 \theta_{13}$):

$$\begin{aligned} \Delta m_{21}^2 &= 7.1 \times 10^{-5} \text{ eV}^2, \\ \Delta m_{32}^2 &= 2.5 \times 10^{-3} \text{ eV}^2, \\ \sin^2 2\theta_{12} &= 0.84, \\ \sin^2 2\theta_{23} &= 1.0, \\ \sin^2 \theta_{13} &= 0.02 && \text{Large } \theta_{13}, \\ \sin^2 \theta_{13} &= 10^{-7} && \text{Small } \theta_{13}, \\ \delta &= 0 && \text{Dirac's phase.} \end{aligned}$$

In addition we also considered two cases of mass hierarchies, the Direct (normal, $m_1 < m_2 \ll m_3$) and the Inverted ($m_3 \ll m_1 < m_2$) ones (however, because the energies of SN neutrinos are relatively small and the Dirac's phase δ is set to zero, there are almost no differences in results of the regeneration in the Earth between these two hierarchies).

4. Detection of supernova neutrinos

We consider three detectors: ICARUS [4], SK [5] and SNO [6]. The positions of these detectors on the Earth are shown in Fig. 1. These detectors have the following feature: in most of the time, when a possible neutrino signal arrives to the Earth, at least one detector is shielded by the Earth (assuming a supernova exploded in the center of our Galaxy), and therefore we will see the regeneration effect in the Earth. All possible processes which contribute to the total number of neutrino interaction in each detector are taken into account. The cross sections for these processes which we use come from [12] and [13].

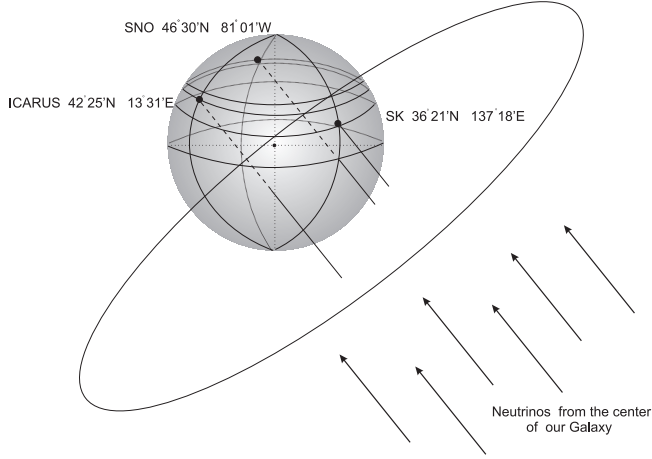


Fig. 1. An example of a possible relative position of ICARUS, SK and SNO detectors and a supernova which exploded in the center of our Galaxy.

5. Results and discussion

The expected total numbers of supernova neutrino interactions N_{SN} , integrated over neutrino energy in the range 0.1 MeV–100 MeV (the whole supernova neutrino energy spectrum), for all possible neutrino processes in ICARUS T600 (an “industrial” ICARUS module filled with 600 tons of liquid argon), SK (32 ktons of light water) and SNO (1 kton of heavy water, 1.7 ktons of light water) detectors are calculated (neutrino oscillations in supernova and the regeneration effect in the Earth have been taken into account). It is assumed that a supernova explosion occurred in the center of our Galaxy, that is 10kpc away from the Earth. The results are presented in Fig. 2 as a function of the distance which neutrinos traveled in the Earth, for four possible combinations of the mass hierarchy and the θ_{13} value.

The main neutrino interactions with detector materials which contribute to the N_{SN} are the following (the minimum and maximum contributions of a particular process, taken for the four considered cases altogether, into the total number of interactions are also given):

ICARUS	$\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^-$	$\sim (87 \div 93)\%$
SK	$\bar{\nu}_e + p \rightarrow n + e^+$	$\sim (76 \div 80)\%$
	$\nu_e + \text{O} \rightarrow \text{F} + e^-$	$\sim (6 \div 10)\%$
SNO	$\bar{\nu}_e + p \rightarrow n + e^+$	$\sim (31 \div 37)\%$
	$\nu_e + d \rightarrow p + p + e^-$	$\sim (12 \div 16)\%$
	$\nu_{\mu,\tau} + d \rightarrow \nu_{\mu,\tau} + p + n$	$\sim (10 \div 12)\%$
	$\bar{\nu}_{\mu,\tau} + d \rightarrow \bar{\nu}_{\mu,\tau} + p + n$	$\sim (8 \div 12)\%$

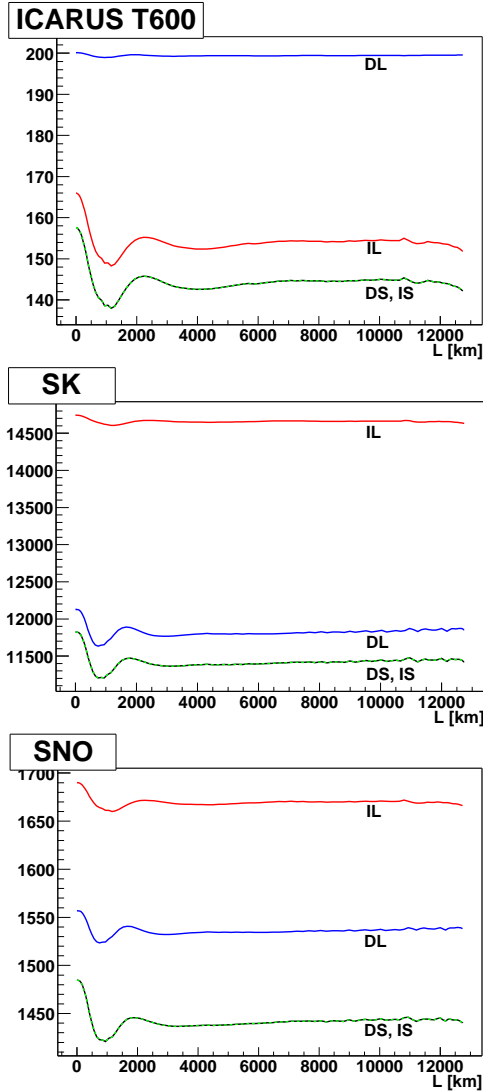


Fig. 2. The expected number of supernova neutrino interactions in ICARUS T600 (600 tons of liquid argon), SK (32 ktons of light water) and SNO (1 kton of heavy water, 1.7 ktons of light water) detectors as a function of the distance, L , neutrinos traveled in the Earth, for different combinations of mass hierarchy and θ_{13} (DL — Direct mass hierarchy and *Large* θ_{13} , IL — Inverted mass hierarchy and *Large* θ_{13} , DS — Direct mass hierarchy and *Small* θ_{13} , IS — Inverted mass hierarchy and *Small* θ_{13}). For details see the description in the text.

It can be seen that, while ν_e interactions dominate in the ICARUS detector, $\bar{\nu}_e$ interactions dominate in the SK and SNO detectors. Taking into account that, in case of *Large* Θ_{13} , neutrino oscillations in supernova make the ν_e spectrum harder (hot) for the Direct mass hierarchy and the $\bar{\nu}_e$ spectrum harder (hot) for the Inverted mass hierarchy (and that all relevant cross sections increase with energy), one gets the corresponding behavior of N_{SN} in Fig. 2 (compare the DL *versus* the IL curves).

Two conclusions are straightforward: the distance traveled by neutrinos in the Earth has only little influence on the value of N_{SN} and, in case of *Small* Θ_{13} , the value of N_{SN} does not depend on the mass hierarchy at all. Finally, the N_{SN} from all three detectors should allow us to draw conclusions about the value of the Θ_{13} and, in case the Θ_{13} is sufficiently large, it should also be possible to say which mass hierarchy is in force.

Last, but not least, it should be noted that, in case of the ICARUS detector, for the purpose of this paper we performed calculations for the currently existing ICARUS T600 (600 tons of liquid argon) module. The final total mass of the ICARUS detector (which will be installed in the underground LNGS Laboratory in Gran Sasso/Italy, see [4]) will be of the order of 3000 tons of liquid argon. That means that the expected total number of supernova neutrino interactions N_{SN} will be five times larger than the one presented in this paper.

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